

The effect of elastic deformation on the minor hysteresis loops of low carbon steel

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Abstract. The effect of elastic tensile deformations on the magnetic permeability of a structural low-carbon steel 20K (0.23 % C, 0.20 % Si, 0.46 % Mn) at various magnetic states was experimentally studied. To obtain these parameters, the measurements of minor hysteresis loops, which begin in the demagnetized state and in the remanent magnetization state, were carried out. The maximum tensile stress equal to 250 MPa that corresponds to 90 % of the conditional yield strength of studied steel. Stress dependences of the initial and reversible magnetic permeabilities as well as differential magnetic permeability along the descending branch of the minor hysteresis loop, which starts in the remanent magnetization state, are non-monotonic. They have extremums at $\sigma = 50\text{--}70$ MPa. However, stress dependences of the sums of those parameters are monotonic. The relative changes reach 25 % at tensile stresses of 250 MPa which make the promise of using the sums of magnetic permeabilities as parameters for assessing the magnitude of tensile stresses.

1. Introduction

Studies of the dependences of the magnetic properties of ferromagnetic materials on the parameters of their stress state make it possible to create methods for assessing the stress-strain state of constructions made from such materials. Approaches associated with magnetization along return curves are common in magnetic non-destructive testing of ferromagnetic materials [1]. A number of papers demonstrate the possibility of using such parameter as a reversible magnetic permeability in the remanent magnetization state μ_{rev} . The permeability μ_{rev} depends not only on the mobility of the domain boundaries but also on the magnetic state of the material, which is determined by the concentration of various magnetic phases in the measured direction, the number and volume of domain boundaries. Dependences of μ_{rev} make it possible to calculate the magnitude of the induced magnetic anisotropy and residual stresses [2, 3]. Reversible permeability could be used to evaluate the remanent life of advanced ferritic steel [4]. However, the dependences μ_{rev} of low-carbon steels on elastic deformations can be non-monotonic [5].

To obtain a unique dependence, the ratio of magnetic permeabilities obtained in different magnetic states can be used. With increase of the tempering temperature of some steels the values of μ_{rev} and initial permeability μ_{init} vary ambiguously [6], and their changes qualitatively coincide, but the ratio $\mu_{\text{rev}} / \mu_{\text{init}}$ changes monotonically with increasing tempering temperature. This is due to the fact that the concentration of magnetic phases at the demagnetized (field $H = 0$, induction $B = 0$) and remanent magnetization ($H = 0$, $B = B_r$) states depends on the tempering temperature differently. There is a high



correlation of the ratio $\mu_{\text{rev}} / \mu_{\text{init}}$ with the value of residual stresses in ferromagnetic materials. Also, the ratio of $\mu_{\text{rev}} / \mu_{\text{init}}$ can be used to estimate the number of loading cycles of metal constructions operating under cyclic loads [7]. It is due to the significant residual compressive stresses appearing in a large number of grains along the tension axis under stress relief after cycling testing [8–11]. The effect of elastic stresses on the structural state has its own specifics and is of interest to study.

The aim of this work is to study the effect of elastic deformations on minor hysteresis loops, including those that begin in the remanent magnetization state, to identify parameters that can be used to develop methods for non-destructive evaluation of the stress-strain state of metal constructions.

2. Materials and experimental procedure

The studies were carried out on flat samples of structural low-carbon steel 20K (0.23 % C, 0.20 % Si, 0.46 % Mn). Magnetic hysteresis loops were measured directly during deformation on a bench consisting of a Tinius Olsen SL-60 hydraulic testing machine and a magneto-measuring complex Remagraph C-500.

Tensile stresses were limited by 250 MPa, which corresponds to 90 % of the conditional yield strength of steel 20 K. To calculate the errors in measured parameters, 10 measurements were performed at each loading point.

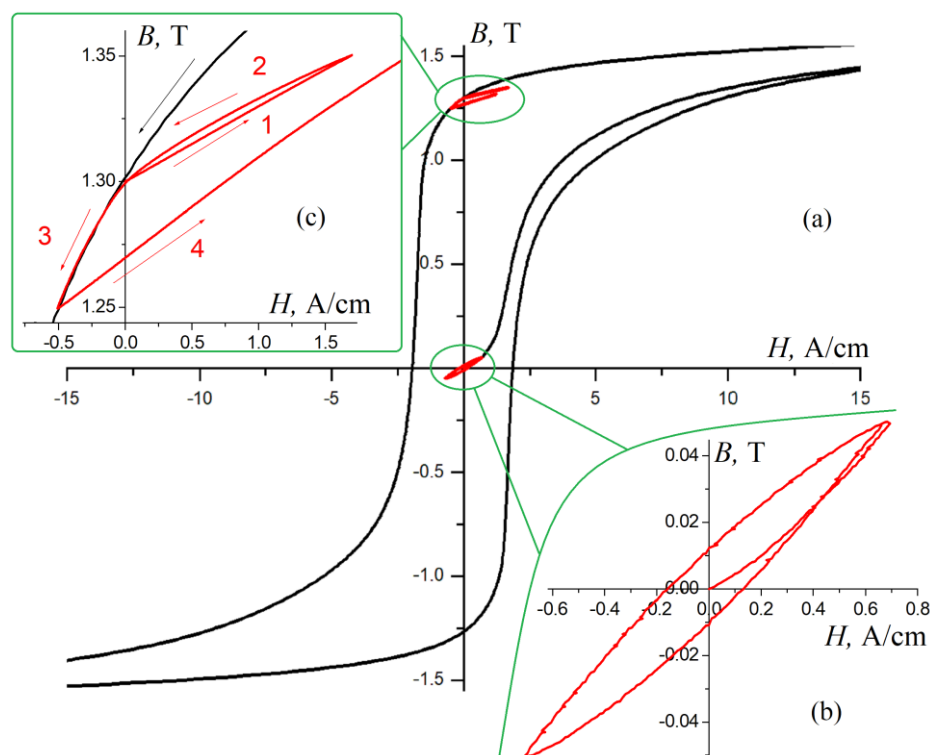


Figure 1. Hysteresis loops: (a) – major, (b) – minor in the demagnetized state, (c) – minor in the remanent magnetization state.

Minor hysteresis loops were measured in the induction range of ± 0.05 T from the starting point of measurement. Figure 1 shows the measured minor hysteresis loops and their location relative to the major hysteresis loop (Figure 1a) for steel 20K in the unloaded state. Parameters μ_{init} and μ_{rev} were calculated from the initial section of magnetization, where $B(H)$ is a linear dependence. The size of this section varies for different stress states. The differential magnetic permeability $\mu_{\text{dif}} = \mu_0 \times dB / dH$ was calculated on the descending branch of the hysteresis (μ_0 is a permeability of free space).

3. Results and discussion

The minor loop in the demagnetized state (Figure 1b) is a symmetric loop in weak fields. It can be described by the Rayleigh law, according to which irreversible magnetization processes are proportional to H^2 . The minor loop in the remanent magnetization state is not symmetrical, as seen in Figure 1c. The following 4 steps can be noted (indicated by numbers in Figure 1c):

At step 1 the dependence of the magnetization on the field in weak fields is close to linear, and this region of ‘linear dependence’ is larger than the same area on the magnetization curve from the demagnetized state.

At step 2 the magnetization reversal curve does not coincide with the magnetization curve, but the residual induction returns to its original value B_r . This can be seen in more detail in Figure 2 – the changes of residual induction are close to zero and are independent of tensile stresses. The scatter of values is due to the measurement error and does not exceed 1.5 % of the magnetization range.

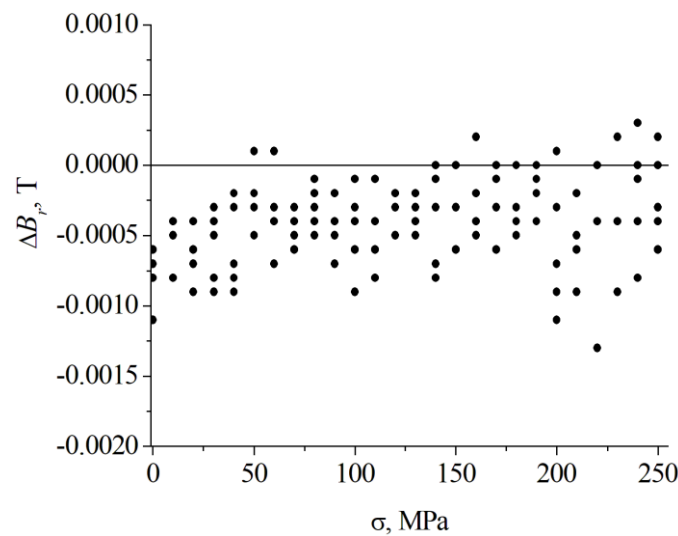


Figure 2. Changes in residual induction after a cycle 1–2 at various tensile stresses.

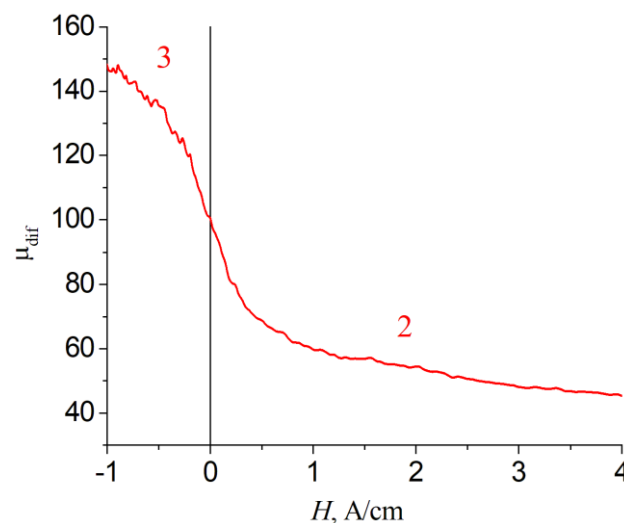


Figure 3. Field dependence of the differential magnetic permeability at steps 2 and 3.

At step 3 the magnetization reversal curve in negative fields coincides with a part of the descending branch of the major hysteresis loop, which is a consequence of the closure of cycle 1–2. The domain

structure at the beginning of step 3 corresponds to the structure in the usual remanent magnetization state: negative fields that have not been previously passed are critical for the motion of domain walls through defects and their overcoming leads to irreversible changes in the magnetization. Therefore, an abrupt increase in the differential magnetic permeability occurs at the boundary between step 2 and step 3 (Figure 3).

At step 4 the return curve that begins with induction ($B_r - 0.05$ T) has a slightly higher permeability compared to μ_{rev} , but the cycle is not closed at the induction ($B_r + 0.05$ T).

Due to the fact that the range of the linear changes $B(H)$ in the remanent magnetization state is greater than in the demagnetized state, the obtained values of μ_{rev} have better repeatability compared to μ_{init} . For steel 20 K both of dependences $\mu_{rev}(\sigma)$ and $\mu_{init}(\sigma)$ are non-monotonic. They have extremums at $\sigma = 50\text{--}70$ MPa (Figure 4a). The effect of stress on permeability is different, which may be due to changes in the sign of magnetostriction at large values of induction, which is typical mainly for low alloy steels [12–15]. So, the ratio μ_{rev} / μ_{init} has a relatively high sensitivity to tensile stresses (Figure 5a). However, this ratio also non-monotonic varies from the value of tensile stresses, and therefore cannot be recommended as a parameter for evaluating the stresses for steel 20 K.

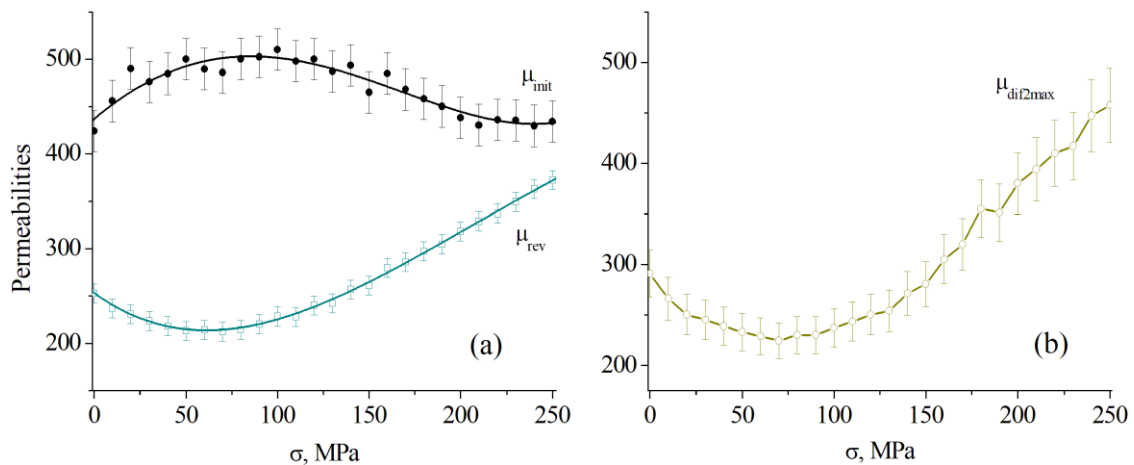


Figure 4. The influence of tensile stresses on the initial and reversible magnetic permeabilities (a) and the value of differential magnetic permeability at zero field (b).

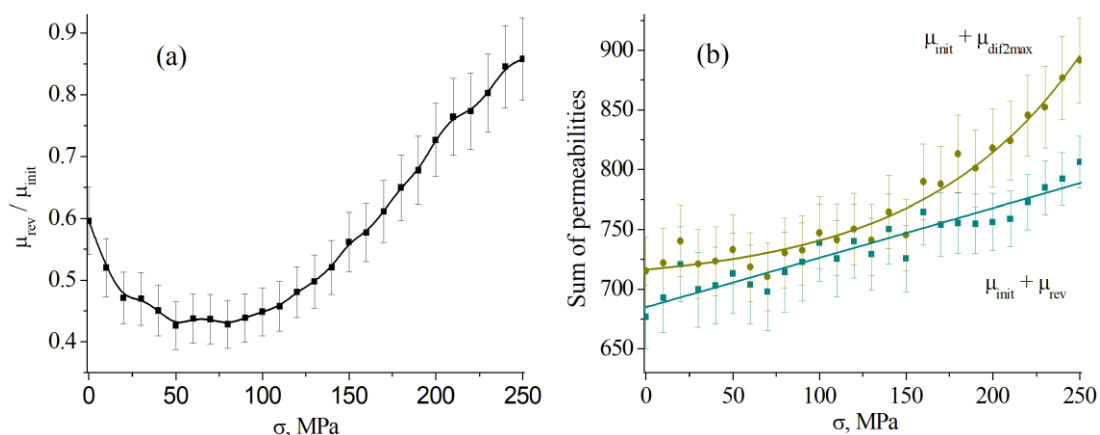


Figure 5. The influence of tensile stresses on the ratio (a) and the sum (b) of the permeabilities.

Figure 3 shows that at step 2, with field decreasing, the differential magnetic permeability monotonically increases, reaching a maximum value of $\mu_{dif2max}$ at $H = 0$. Figure 4b shows that the parameter $\mu_{dif2max}$ varies significantly from the action of large tensile stresses. The form of the

dependence $\mu_{\text{dif2max}}(\sigma)$ is qualitatively similar to $\mu_{\text{rev}}(\sigma)$, and the largest differences are observed at $\sigma > 150$ MPa. These differences characterize the difference in the mobility of domain walls in the remanent state before and after exposure to a weak magnetic field.

Due to the fact that the extremum is the maximum in the dependence $\mu_{\text{init}}(\sigma)$, and it is the minimum in the dependences $\mu_{\text{rev}}(\sigma)$ and $\mu_{\text{dif2max}}(\sigma)$, the permeability sums can be used as parameters for assessing tensile stresses (Figure 5b). The sum of $\mu_{\text{init}} + \mu_{\text{rev}}$ linearly (correlation coefficient is 0.95) increases with increasing tensile stresses.

The dependence of the sum $\mu_{\text{init}} + \mu_{\text{dif2max}}$ can be divided into two parts. At the initial stage, tension has little effect on the amount of permeability and the changes fit into the measurement error. At the stress value of more than 150 MPa, a monotonic increase in the sum $\mu_{\text{init}} + \mu_{\text{dif2max}}$ occurs. The relative changes reach 25 % at tensile stresses of 250 MPa. Thus, the growth of $\mu_{\text{init}} + \mu_{\text{dif2max}}$ can be used as an indicator of a significant magnitude of tensile stresses (for steel 20 K, $\sigma = 150$ MPa corresponds to 0.5 yield strength).

However, when using such parameters, it must be taken into account that the relative error of the sum of permeabilities is the sum of the relative errors of the individual components, and the relative error of measurement of μ_{dif2max} is larger than for μ_{rev} .

4. Conclusion

The results of studies of the effect of tensile stresses on the characteristics of minor hysteresis loops of the steel 20 K obtained in a statically demagnetized and remanent magnetization states have shown the promise of using the sums of magnetic permeabilities as parameters for assessing the magnitude of tensile stresses.

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